

Breakdown Voltage Limitations, Impact Ionization, and Interband Tunneling in InP/GaAsSb/InP Type-II NpN DHBTs

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Abstract

We investigate the breakdown limitations of staggered ("type-II") lineup InP/GaAsSb/InP N-p-N double heterojunction bipolar transistors (DHBTs). These devices generally feature an abnormally low open-emitter BV_{CBO} despite the low electron impact ionization coefficient for electrons in the InP collector layer. We show that the high apparent BV_{CEO}/BV_{CBO} ratio can be associated with the onset of interband (Zener) tunneling across the narrow energy gap interface layer arising from the staggered band alignment at the reverse biased GaAsSb-InP base-collector heterojunction. We also demonstrate that InP/GaAsSb DHBTs can be operated above BV_{CEO} (and the apparent BV_{CBO}), and up to voltages approaching the impact ionization limited BV_{CBO} .

Introduction

InP/GaAsSb/InP N-p-N double heterojunction bipolar transistors (DHBTs) have demonstrated outstanding dynamic performance characteristics for simple manufacturable structures involving only layers of uniform composition and abrupt interfaces at the emitter and collector heterojunctions. InP/GaAsSb/InP DHBTs derive their performance advantages from a band lineup [1, 2] that proves favorable for high current density operation, and from the ability to dope MOCVD-grown GaAsSb base layers with carbon acceptors without being subject to severe hydrogen passivation effects [3]. This key combination of properties has enabled the development of high-speed InP/GaAsSb DHBTs with f_T and f_{MAX} cutoff frequencies simultaneously exceeding 300 GHz while maintaining common-emitter breakdown voltage values $BV_{CEO} > 6$ V with a 2000 Å InP collector [4, 5]. The $f_T \times BV_{CEO}$ product thus exceeds 1800 GHz-V. In addition of clarifying the transistor physical limitations, the study of carrier multiplication and breakdown voltages in InP DHBTs recently acquired increased importance because of a new emphasis on the development of aggressively scaled thin-collector transistors.

InP/GaAsSb/InP DHBTs do show good common-emitter breakdown voltages BV_{CEO} in thin collector structures because of the relatively low electron impact ionization rate in InP. However, InP/GaAsSb/InP DHBTs are also characterized by unexpectedly low open-emitter base-collector reverse breakdown voltages BV_{CBO} , and the resulting BV_{CEO}/BV_{CBO} ratio is found to approach unity when relatively highly doped collector layers are used to enable high-current transistor operation. This unusual behavior is illustrated in Fig. 1 below for several collector structures grown and fabricated at the SFU CSDL. The solid curves show the open-base collector-to-emitter BV_{CEO} breakdown characteristics, and the dashed curves show the open-emitter base-collector BV_{CBO} breakdown characteristics. It is worth noting that whereas devices fabricated at SFU were not passivated, a similar behavior is also observed on passivated InP/GaAsSb/InP DHBTs fabricated at Agilent—clearly, the low experimental BV_{CBO} values are not simply caused by parasitic surface leakage effects.

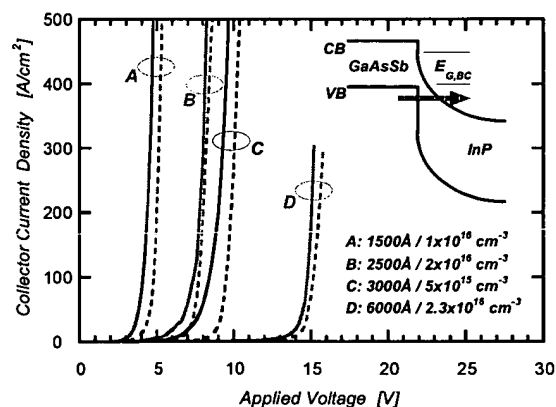


Fig. 1: Superposed plots of open-base common-emitter breakdown characteristics (BV_{CEO} , solid lines) and open-emitter base/collector breakdown characteristics (BV_{CBO} , dashed lines) for four typical collector designs. The devices were not passivated. A similar behavior is observed on passivated transistors fabricated at Agilent. The inset shows the interband tunneling path for the base/collector breakdown.

The issue of a high BV_{CEO}/BV_{CBO} ratio in InP/GaAsSb/InP DHBTs has not previously been discussed in the literature,

and it is worthy of investigation from a comparative technology point of view, and because conventional transistor theory suggests that BV_{CBO} should be significantly larger than BV_{CEO} .

Textbook descriptions of carrier multiplication in reverse-biased semiconductor junctions rely on the so-called Miller approximation for the carrier multiplication coefficient M

$$M = \frac{1}{1 - \left(\frac{V_R}{V_{BR}} \right)^n}, \quad (1)$$

where the exponent n is determined empirically and usually ranges over $2 < n < 6$. The application of Miller's approximation in the context of bipolar transistors leads to the well-known relation

$$\frac{BV_{CEO}}{BV_{CBO}} = \left[\frac{1}{\beta_F + 1} \right]^{1/n}, \quad (2)$$

and yields a breakdown voltage ratio BV_{CEO}/BV_{CBO} ranging from 0.10 to 0.67 for common-emitter current gain values $10 < \beta_F < 100$, when the exponent n ranges from 2 to 6. Evidently, the empirical nature of Miller's approximation obscures the physical processes that determine the separation between BV_{CEO} and BV_{CBO} .

The conventional treatment of carrier multiplication in bipolar transistors outlined in equations (1-2) predicts a far lower BV_{CEO}/BV_{CBO} ratio than what is experimentally observed in InP/GaAsSb/InP DHBTs, as shown in Fig. 1 and Table I. Even low gain values such as $\beta_F = 10$ lead to $BV_{CEO}/BV_{CBO} = 0.79$ when an extreme value of $n = 10$ is assumed, highlighting the inadequacy of the classical understanding of breakdown in BJTs as far as type-II heterojunction collectors are concerned.

The purpose of the present work is thus to document and clarify the physical origins of the $BV_{CEO} - BV_{CBO}$ characteristics in N-p-N InP/GaAsSb/InP DHBTs. We show below that impact ionization accounts very well for the observed BV_{CEO} values, but that ionization alone would result in far larger BV_{CBO} values. We also show that the low measured collector-base BV_{CBO} breakdown voltage values can be attributed to interband tunneling associated with the reduced energy at the staggered base/collector heterojunction. Finally, we demonstrate that InP/GaAsSb/InP

DHBTs can be operated well above BV_{CEO} (and the interband tunneling breakdown voltage we call BV_Z here).

Breakdown Voltages and Impact Ionization

We wish to relate impact ionization to the transistor breakdown voltages, and proceed by computing the ionization integral through the InP collector for electron initiated ionization: our calculation includes the effects of secondary hole impact ionization, and non-local ionization effects for electrons through the inclusion of a dead space region of length x_{th} defined as the distance required to ballistically accelerate an electron up to the ionization threshold energy E_{th} .

The effect of secondary ionization due to the generated holes must be included because the hole ionization coefficient in InP is reported to be greater than the electron ionization coefficient in high electric fields, $\alpha_p(E) > \alpha_n(E)$. The relevant ionization integral is given by [6]

$$S = 1 - \frac{1}{M} = \left(1 + \int_0^{x_{th}} \alpha_p dx \right) \cdot \int_{x_{th}}^{W_C} \alpha_n \exp \left[- \int_{x_{th}}^x (\alpha_n - \alpha_p) dx' \right] dx \quad (3)$$

where we use the $\alpha_n(E)$ and $\alpha_p(E)$ values recently recommended by Saleh *et al.* [7] for the InP electron and hole ionization coefficients as a function of the electric field, as well as their recommended value for the electron ionization energy threshold $E_{th} = 2.05$ eV. We assume non-local effects are negligible for holes because they experience smoothly varying potentials deep in the collector region.

It is well known that the common-emitter breakdown voltage $V_{CE} = BV_{CEO}$ achieved with $I_B = 0$ corresponds to the condition $\alpha_F \times M = 1$ (or $S_M = 1 - \alpha_F$, where α_F is the common-base current gain), while the BV_{CBO} breakdown condition in turn corresponds to $S_M = 1$, or $M \rightarrow \infty$. Thus, BV_{CEO} is reached under *weak* carrier multiplication with $M \sim 1$ (especially in high current gain transistors), while BV_{CBO} corresponds to full avalanche multiplication and is independent of device gain. Clearly, the *sharpness* of the $S(V_{CB})$ function determines the BV_{CEO}/BV_{CBO} ratio in various material systems, and (3) along with $\alpha_n(E)$ and $\alpha_p(E)$ provide the physical insight which is lacking from the Miller multiplication approach. The preceding statement will hold as long as the dominant mechanism setting BV_{CEO} and BV_{CBO} is impact ionization.

For all cases below, we assume a common-emitter current gain $\beta_F = 50$ corresponding to $\alpha_F = 0.98$. Table I shows the measured BV_{CEO} and BV_{CBO} for the devices of Fig. 1 (and two others omitted from Fig. 1 for clarity), and includes the values predicted by the ionization integral (3). We note that the agreement is quite good between the experimental and computed BV_{CEO} values (maximum and average errors of 11% and 5%, respectively), and we attribute the small residual discrepancies to variations in α_F and in the collector doping-thickness product across devices. For BV_{CBO} , however, calculated values from equation (3) assuming impact ionization are significantly above the experimental values, with predicted BV_{CEO}/BV_{CBO} values of ~ 0.60 compared to experimental values ≥ 0.90 . The discrepancy suggests that an alternate mechanism may be responsible for the low BV_{CBO} values measured in InP/GaAsSb/InP DHBTs.

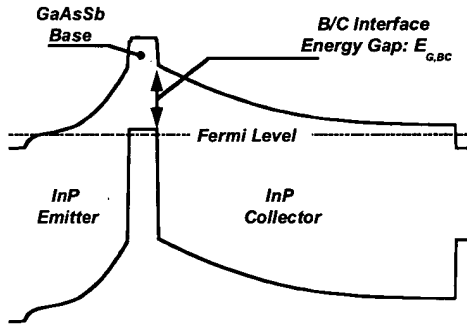


Fig. 2: Equilibrium band diagram for N-p-n InP/GaAsSb/InP DHBT showing a reduced energy gap at the B/C heterojunction as a result of the staggered band alignment between GaAsSb and InP. Increasing the reverse bias V_{CB} across the B/C junction reduces the tunneling distance between the base valence band edge and the InP conduction band in the collector.

Consideration of the B/C heterojunction band diagram shown in Fig. 2 reveals that interband (Zener) tunneling is likely to occur at larger reverse biases between the p^+ GaAsSb base valence band edge and the InP conduction band edge because the staggered band lineup results in a narrow effective gap at the B/C junction. The interband process becomes important because the narrow gap interface region coincides with the region of maximum electric field at the B/C junction. Based on the measured band lineup of $\Delta E_C = 0.10 - 0.15$ eV between InP and GaAs_{0.51}Sb_{0.49} [1, 2], and with a room temperature energy gap of 0.72 eV for the base layer, the effective energy gap at the B/C heterojunction is only 0.57 – 0.62 eV. Table I also includes the calculated Zener breakdown voltage BV_Z (also defined at $J_C = 500$ A/cm², unless otherwise indicated). Our computation assumes $E_{G,BC} = 0.57$ eV, and $m = 0.07m_0$ for

the electron tunneling effective mass in InP, and we follow Ito *et al.* [8] with:

$$J_Z = \left(\frac{q}{2\pi} \right)^3 \cdot \sqrt{\frac{2m}{E_{G,BC}}} \times \frac{(E_{BC,max} \cdot V_{CB})}{\hbar^2} \cdot \exp \left[-\frac{\pi \sqrt{2m} E_{G,BC}^3}{4\hbar q E_{BC,max}} \right] \quad (4)$$

Clearly, the resulting BV_Z values are generally in good agreement with the experimentally observed BV_{CBO} values of Table I without using any adjustable parameters (the maximum and average errors are equal to 18.3% and 7.6%, respectively), despite the exponential dependence of the interband tunneling current upon the energy gap value and the electric field value at the B/C junction. The type-II B/C band discontinuity can therefore be viewed as a tuning parameter that is intimately involved in the measured BV_{CBO} limitation of InP/GaAsSb/InP DHBTs because the ΔE_C at the InP/GaAsSb interface depends on the As- mole fraction in the base layer [2]. Clearly, the use of pseudomorphic base layers could affect both the energy gap at the heterojunction $E_{G,BC}$, and the density of initial available states for tunneling from the base layer.

In general we find that the Zener breakdown condition falls between the computed impact ionization breakdown voltages $BV_{CEO} < BV_Z < BV_{CBO}$ in InP/GaAsSb/InP DHBTs if a uniformly doped collector is used with a nearly lattice-matched GaAs_xSb_{1-x} base layer.

Practical Implications

The reduced apparent BV_{CBO} values resulting from the interband tunneling process at the type-II B/C junction might at first sight appear to limit the maximum allowable bias in InP/GaAsSb/InP DHBTs. It is therefore important to explore whether the interband breakdown process imposes serious limitations on transistor operation when useful current densities flow through the collector.

Examination of equation (4) indicates that the negative traveling space charge associated with a collector current density J_C reduces the peak electric field at the B/C junction, and should exponentially suppress the interband breakdown mechanism. In principle, three terminal transistor operation with a significant collector current density should therefore be possible beyond BV_{CEO} and BV_Z if the device is appropriately biased.

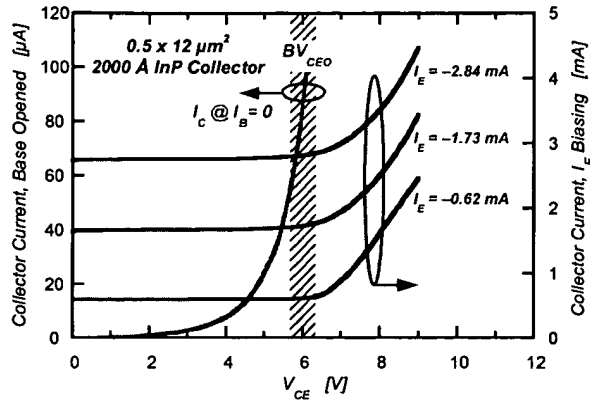


Fig. 3: Superposition of the static common-emitter I_C - V_{CE} characteristics (with a current source bias) and the open-base common-emitter BV_{CEO} breakdown characteristics. Clearly, the BV_{CEO} and BV_{CBO} "breakdown" voltages can be exceeded by as much as 50%, even with $J_C > 66 \text{ kA/cm}^2$.

Fig. 3 shows a 2000 Å InP collector transistor with a $BV_{CEO} = 6 \text{ V}$ operated well above its common-emitter breakdown voltage when biased with a constant emitter current I_E . Fig. 3 shows that BV_{CEO} can be exceeded by at least 50% with $J_C > 66 \text{ kA/cm}^2$, without causing any apparent short term degradation. The figure also reveals that the collector current increase beyond BV_{CEO} is weaker at higher bias currents because of the reduced electric field at the B/C junction. It is noteworthy that the device shown in Fig. 3 did not sustain damage until a bias of $V_{CE} = 10 \text{ V}$ was applied. Therefore, InP/GaAsSb/InP DHBTs can in fact be operated up to voltages approaching the BV_{CBO} limit determined by impact ionization. InP/GaAsSb/InP DHBTs thus share this capability with silicon-based bipolar transistors [9]. It is still not clear at this time if prolonged reliable operation above BV_{CEO} will be possible with InP collector DHBTs, but transport phenomena do not provide a hard limitation through $S(V_{CB})$ in equation (3).

Acknowledgments

This work was supported by an NSERC Strategic Grant and by grants from *Agilent Laboratories* (Palo Alto, CA) and *Nortel Networks* (Ottawa, ON).

References

- [1] J. Hu, X. G. Xu, J. A. H. Stotz, S. P. Watkins, A. E. Curzon, M. L. W. Thewalt, N. Matine, and C. R. Bolognesi, "Type II photoluminescence and conduction band offsets of GaAsSb/InGaAs and GaAsSb/InP heterostructures grown by metalorganic vapor phase epitaxy," *Appl. Phys. Lett.*, vol. 73, pp. 2799-2801, 1998.
- [2] M. Peter, N. Herres, F. Fuchs, K. Winkler, K.-H. Bachem, and J. Wagner, "Band gaps and band offsets in strained GaAs_{1-x}Sb_x on InP grown by metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 74, pp. 410-412, 1999.
- [3] S. P. Watkins, O. J. Pitts, C. Dale, X. G. Xu, M. W. Dvorak, N. Matine, and C. R. Bolognesi, "Heavily carbon-doped GaAsSb grown for HBT applications," *J. Cryst. Growth*, vol. 221, pp. 59-65, 2000.
- [4] M. W. Dvorak, C. R. Bolognesi, O. J. Pitts and S. P. Watkins, "300 GHz InP/GaAsSb/InP double HBTs with high current capability and $BV_{CEO} > 6 \text{ V}$," *IEEE Electron Dev. Lett.*, vol. 22, pp. 361-363, 2001.
- [5] C. R. Bolognesi, M. W. Dvorak, N. Matine, O. J. Pitts and S. P. Watkins, "Ultrahigh performance staggered lineup ("type-II") InP/GaAsSb/InP NpN double heterojunction bipolar transistors," *Japanese Journal of Applied Physics, Part 1*, vol. 41, pp. 1131-1135, 2002.
- [6] M. H. Woods, W. C. Johnson and M. A. Lampert, "Use of a Schottky barrier to measure impact ionization coefficients in semiconductors," *Solid State Electronics*, vol. 16, pp. 381-394, 1973.
- [7] M. A. Saleh, M. M. Hayat, P. P. Sotiropoulos, A. L. Holmes, J. C. Campbell, B. E. A. Saleh, and M. C. Teich, "Impact-ionization and noise characteristics of thin III-V avalanche photodiodes," *IEEE Trans. Electron Devices*, vol. 48, pp. 2722-2731, 2001.
- [8] M. Ito, T. Kaneda, K. Nakajima, Y. Toyama and H. Ando, "Tunneling currents in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ homojunction diodes and design of InGaAs/InP hetero-structure avalanche photodiodes," *Solid-State Electronics*, vol. 24, pp. 421-424, 1981.
- [9] M. Rickelt, H.-M. Rein and E. Rose, "Influence of impact-ionization-induced instabilities on the maximum usable output voltage of Si-bipolar transistors," *IEEE Trans. Electron Devices*, vol. 48, pp. 774-783, 2001.

TABLE I: MEASURED AND COMPUTED BREAKDOWN VOLTAGES

InP Collector			Measured			Computed				
RUN #	W_C (Å)	N_C (cm^{-3})	BV_{CEO} (V)	BV_{CBO} (V)	BV_{CEO}/BV_{CBO} —	BV_{CEO} (V)	BV_{CBO} (V)	BV_{CEO} Error —	BV_{ZENER} (V)	BV_{ZCBO} Error —
3250	1500	1×10^{16}	4.7	5.3	0.89	5.0	9.0	+6.3%	5.1	-3.8%
3251	1500	2×10^{16}	5.4	6.0	0.90	5.1	9.0	-5.6%	4.9	-18.3%
3252	2500	2×10^{16}	8.2	8.6	0.95	8.2	13.6	0.0%	8.0	-6.9%
2601	3000	5×10^{15}	9.6	10.6	0.91	9.7	15.9	+1.0%	10.3	-2.8%
2965	6000	2.3×10^{16}	15.3	15.7	0.97	17.0	28.0	+11.1%	14.7	-6.4%